MODEL FOR ULTRAFAST CARRIER SCATTERING IN SEMICONDUCTORS

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Interim Report

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14. ABSTRACT

Overall objective of this research effort is to understand and explain ultrafast carrier scattering dynamics in semiconductor heterostructures. Specific research objectives are: To develop a screened semiconductor bloch formalism to provide the force-balance equation with a friction force that determines electron drift velocity, and to establish screened semiconductor bloch equations to study the dynamics of electron impurity, roughness, phonon, electron scattering, and dynamics of optical pumping.

15. SUBJECT TERMS
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Air Force Applications of Project:

One of the major products of FLTCs 2.6.3 and 7.2.1 is a lightweight, reconfigurable electro-optic sensor system (2.6.3.2 and 7.2.1.2). Aimed at that product, we are investigating the possibilities of incorporating a protection layer, an optical signal amplification layer, a detection layer, a solid-state cooling layer, and a high-speed readout electronics layer all monolithically integrated within a single pixel of a semiconductor focal plane array (for vast reductions in size and weight). When completed, the microscopic theory that arises from this renewed project will be applicable to each of the various layers of the super-pixel device for both further understanding of the quantum mechanical processes involved, as well as for greatly improving the performance of each layer. This theory will be applied to kinetic studies of laser damage of semiconductor photodetectors, in order to describe and understand all radiation damage mechanisms and the role of impact ionization on the generation of multi-excitons so that methods of mitigation can be developed for the protection layer of the monolithic sensor. This theory will be applied to describing and predicting the optical control of scattering-induced dephasing for optical signal amplification in photodetectors using electronic quantum coherence, as well as for noise reduction in both detectors and electronics. This theory will be applied to the photo-carrier transport processes involved within the detection layer, for improving performance by minimizing dark-current and maximizing the photo-current at the same time. This theory has already been applied to photoluminescent cooling of detectors; a vibrationless, low-cost, extremely low-volume and weight on-chip solid-state cryogenic cooling scheme for space sensors. Finally, this theory will be applicable to high-power and ultrafast electronics development for on-chip FPA imaging processing.

Progress for Oct 2008 to Sep 2009:

We obtained numerical results for steady-state and time-dependent currents as well as for a long-time average current in strong nonlinear dc and ac electric fields for an electron gas in a one-dimensional quantum-dot superlattice. A microscopic model was employed for the scattering of electrons by phonons and static impurities by means of the Boltzmann equation method. The dc results were favorably compared with recent exact analytic results based on a relaxation-time model for electron-phonon scattering. Our results demonstrated the different roles played by elastic and inelastic scattering on the damped Bloch oscillations as well as the nonlinear steady-state current and their opposite roles on the damped dynamical localization. We also found a suppression of dynamical localization by strong Bloch oscillations and features in the Esaki-Tsu peaks in the presence of an ac electric field when electron scattering was included. On the basis of a nonequilibrium electron distribution obtained from the Boltzmann equation, a self-consistent-field approach was employed to establish a general formalism for the optical response of current-driven electrons in both the linear and nonlinear regimes to a 1D quantum-dot superlattice. The dc-field dependences of both the peak energy and peak strength in the absorption spectrum for a 1D quantum-dot superlattice were calculated, from which we found: (1) both the peak energy and its strength were significantly reduced with increasing dc electric field; and (2) the peak energy and peak strength were anomalously enhanced by raising the temperature for the nonlinear transport of electrons when a strong dc electric field was applied.

1

The coupled force-balance and scattering equations were derived and applied to study nonlinear transport of electrons subjected to a strong dc electric field in an elastic-scattering-limited quantum wire. Numerical results demonstrated both field-induced heating-up and cooling-down behaviors in the non-equilibrium part of the total electron-distribution function by varying the impurity density or the width of the quantum wire. The asymmetric distribution function that was obtained in momentum space invalidates the application of the energy-balance equation to our quantum-wire system in the center-of-mass frame. The experimentally observed suppression of mobility by a driving field for the center-of-mass motion in the quantum-wire system was reproduced [see K. Tsubaki et al., Electr. Lett. **24**, 1267 (1988); M. Hauser et al., Sci. Technol. **9**, 951 (1994)]. In addition, the thermal enhancement of mobility in the elastic-scattering-limited system was demonstrated, in accordance with a similar prediction made for graphene nanoribbons [see T. Fang et al., Phys. Rev. B **78**, 205403 (2008)]. This thermal enhancement was found to play a more and more significant role with higher lattice temperature and becomes stronger for a low-driving field.

We exactly solved the Boltzmann equation for nonlinear electron transport in a quantum wire when impurity and phonon scattering coexist. Based on the calculated non-equilibrium distribution of electrons in momentum space, the scattering effects on both the non-differential and differential mobilities of electrons as functions of temperature and dc field were demonstrated. The non-differential mobility of electrons switches from a linearly increasing function of temperature to a parabolic-like temperature dependence as the quantum wire is tuned from an impurity-dominated system to a phonon-dominated one [see T. Fang, et al., Phys. Rev. B **78**, 205403 (2008)]. In addition, we obtained a maximum in the dc-field dependence of the differential mobility of electrons. The low-field differential mobility is dominated by impurity scattering, whereas the high-field differential mobility is limited by phonon scattering [see M. Hauser, et al., Semicond. Sci. Technol. **9**, 951 (1994)]. Once a quantum wire is dominated by elastic scattering, the peak of the momentum-space distribution function becomes sharpened and both tails of the equilibrium electron distribution centered at the Fermi edges are raised by the dc field after a redistribution of the electrons is fulfilled in a symmetric way. If a quantum wire is dominated by inelastic scattering, on the other hand, the peak of the momentum-space distribution function is unchanged while both shoulders centered at the Fermi edges shift leftward correspondingly with increasing dc field through an asymmetric redistribution of the electrons [see C. Wirner, et al., Phys. Rev. Lett. **70**, 2609 (1993)].

We also investigated the effects of the spin–orbit interaction (SOI) and a plane-perpendicular magnetic field on the conductivity of a two-dimensional electron system in the presence of a one-dimensional electrostatic modulation. The calculations were performed when a low-intensity, low-frequency external electric field was applied. The Kubo formula for the conductivity was employed in the calculation. The single-particle eigenstates which depend on the strengths of the magnetic field, the SOI and the modulation potential, were calculated and

then used to determine the conductivity. We obtained numerical results for the conductivity along the channels as well as the tunneling conductivity perpendicular to the constrictions as functions of the modulation potential, the SOI, and the magnetic field. We demonstrated that the effect of finite frequency is related to the reduction of both the longitudinal and transverse conductivities.

Publications between Oct 2008 and Sep 2009:

1. D. H. Huang, S. K. Lyo, and G. Gumbs: "*Block oscillation, dynamical localization, and optical probing of electron gases in quantum-dot superlattices in high electric fields*", Phys. Rev. B <u>79</u>, 155308 (2009).
2. D. H. Huang and G. Gumbs: "*Coupled force-balance and scattering equations for nonlinear trasport in quantum wires*", Phys. Rev. B <u>80</u>, 033411 (2009).
3. **G. Gumbs and D. H. Huang: "*Magnetoquantum transport in a modulated 2D electron gas with spin-orbit interaction*", Phys. Lett. A <u>373</u>, 2506-2515 (2009).**

Progress for Oct 2009 to Sep 2010:

We calculated the surface response function and the image potential of a system of layered two-dimensional (2D) electron gas structures. A point charge was placed at a distance away from the surface which lies in the *xy*-plane. These 2D layers were coupled through the Coulomb interaction and there was no interlayer electron hopping. The separation between adjacent layers was adjusted to investigate the roles which the layer separation and the number of layers play on both the surface response function and the image potential. Specifically, we considered the system composed of graphene layers or the layered 2D electron gas (EG) formed at the interface of a semiconductor heterostructure such as GaAs/AlGaAs. We showed that the image potential for graphene is qualitatively the same as for the 2DEG. We examined the way in which the image potential was modified by applying a one-dimensional (1D) periodic electrostatic potential (through a gated grating for modulation). The results indicated that the charge screening for graphene was not much different than in the 2DEG.

We investigated the effects of the spin–orbit interaction (SOI) and a plane-perpendicular magnetic field on the conductivity of a 2D electron system in the presence of a 1D electrostatic modulation. The calculations were performed when a low-intensity, low-frequency external electric field was applied. The Kubo formula for the conductivity was employed in the calculation. The single-particle eigenstates which depend on the strengths of the magnetic field, the SOI and modulation potential, were calculated and then used to determine the conductivity. We obtained numerical results for the conductivity along the channels as well as the tunneling conductivity perpendicular to the constrictions as functions of the modulation potential, the SOI and the magnetic field. We demonstrated that the effect of finite frequency was related to the reduction of both the longitudinal and transverse conductivities.

We calculated the energy eigenvalues, the spin-split excitation gap (energy separation between the spin-triplet excited state and the spin-singlet ground state) and the concurrence for two interacting electrons captured in a quantum dot (QD) formed by a gigahertz electron pump which was modeled by harmonic confining potentials. From our calculations we found a peak in the QD size dependence of the energy level for the spin-singlet ground state, indicating the effect due to Coulomb blockade. In addition, we observed a local minimum in the QD size dependence of the spin-split excitation gap for a relatively narrow quasi-1D channel formed from an etched wire, but a strong positive peak for the spin-split excitation gap in its QD size dependence with a relatively wide 1D channel. From the existence of a robust spin-split excitation gap against both thermal fluctuation due to finite (low) temperatures and the nonadiabatic effect due to fast barrier variations, we predicted a spin-entangled electron pair inside the QD with a weak coupling to external leads. An interference-type experiment which employed a gate-controlled electron pump and a beam splitter was proposed to verify this prediction. For the electron pump, a sinusoidal radio-frequency signal was applied to the entrance gate of a two-gated system over a narrow channel etched in a GaAs/AlGaAs heterostructure, where the measured current within the channel showed plateaus at *Nef* with *N = 1, 2, . . .* being the number of captured electrons in a QD and *f* the frequency of the sinusoidal signal.

Finally, we studied the Klein paradox in zigzag (ZNR) and anti-zigzag (AZNR) graphene nanoribbons. Due to the fact that ZNR (the number of lattice sites across the nanoribbon = *N* is even) and AZNR (*N* is odd) configurations are indistinguishable when treated by the Dirac equation, we supplemented the model with a pseudo-parity operator whose eigenvalues correctly depend on the sublattice wavefunctions for the number of carbon atoms across the ribbon, in agreement with the tight-binding model. We showed that the Klein tunneling in zigzag nanoribbons is related to conservation of the pseudo-parity rather than pseudo-spin as in infinite graphene. The perfect transmission in the case of head-on incidence was replaced by perfect transmission at the center of the ribbon and the chirality was interpreted as the projection of the pseudo-parity on momentum at different corners of the Brillouin zone.

Publications between Oct 2009 and Sep 2010:
4. D. H. Huang and G. Gumbs, *Comparison of inelastic and quasi-elastic scattering e_ects on nonlinear electron transport in quantum wires*, J. Appl. Phys. **107**, 15 April (2010).
5. O. Roslyak, A. Iurov, G. Gumbs and D. H. Huang, *Unimpeded tunneling in grapheme nanoribbons*, J. Phys.: Condensed Matter **22**, 165301 (2010).
6. G. Gumbs, D. H. Huang, M. D. Blumenthal, S. J. Wright, M. Pepper and Y. Abranyos, *Spin-split excitation gap and spin entanglement of a pair of interacting electrons in a dynamical quantum dot*, Semicond. Sci. Technol. **24**, 115001 (2009).
7. G. Gumbs, D. H. Huang and P. M. Echenique, *Comparing the image potentials for intercalated graphene with a 2DEG with and without a gated grating*, Phys. Rev. B 79, 035410 (2009).

Recently-Submitted Papers:
1. O. Roslyak, G. Gumbs and D. H. Huang, *Tunable band structure effects on ballistic transport in graphene nanoribbons*, Submitted to Solid State Communications.
2. G. Gumbs, A. Balassis, and D. H. Huang, *Energy bands, conductance and thermoelectric power for ballistic electrons in a nanowire with spin-orbit interaction*, Submitted to Physical Review B.

Proposed Future Technical Work:

(1) Solve the Boltzmann equations for the coupled electron-phonon system in quantum-dot superlattices and quantum wires to study the thermoelectric effect from both electron diffusion and phonon drag in the nonlinear transport regime;

(2) Generalize our Boltzmann theory through incorporation of the optical-coherence effect from a spatially-uniform pump laser by coupling the Boltzmann equation to the Bloch equations;

(3) Extend our theory to deal with a spatially-non-uniform pump laser by coupling the Maxwell equations to the Bloch equations;

(4) Generalize our formalism by expanding the GaAs-based semiconductor system to Dirac particles in graphene and graphene nanoribbons;

(5) Generalize our formalism by including the Rashba spin-orbit interaction in electron nonlinear transport;

(6) Apply the Boltzmann scattering equation to the study of the role of impact ionization on multi-exciton generation under a strong pump laser with high excess photon energy, which can be used for solar cells integrated with photodetectors in self-powered operation.

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